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Title: Applications of laser-driven ion beams

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Applications of laser-driven ion beams

presented by:

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LANL & Collaborating Institutions

(Acknowledgements throughout the talk)

presented to:

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Saint Malo, France

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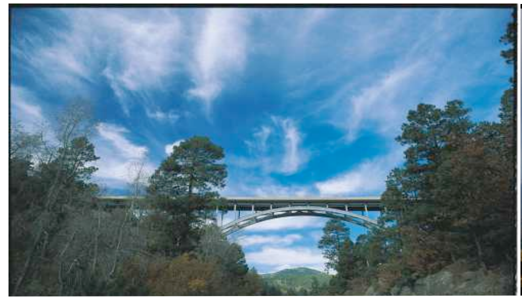

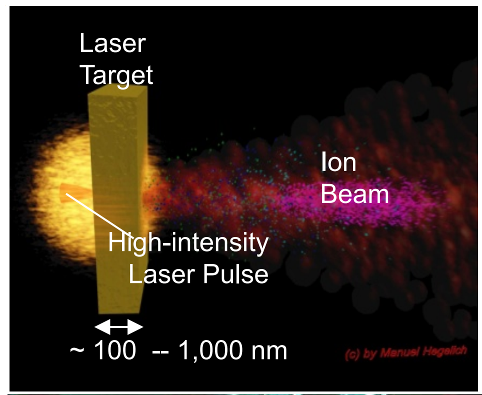

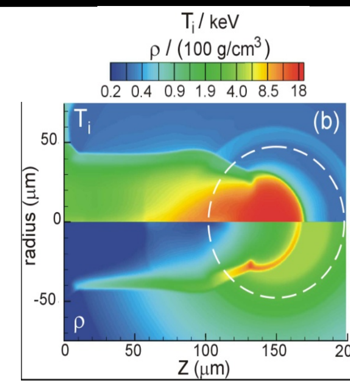

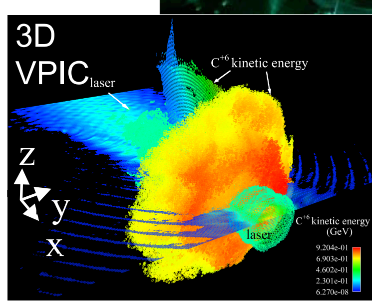

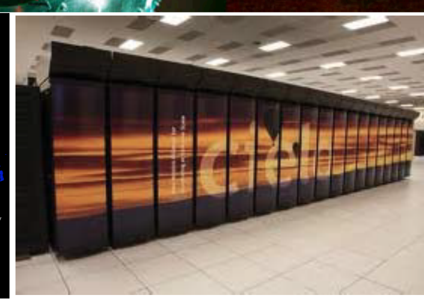

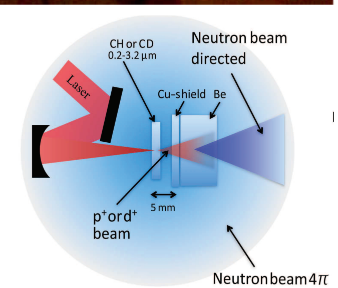

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  - **B. J. Albright**, **A. Favalli**, D. C. Gautier, K. Falk, A. Favalli J. C. Fernández, N. Guler, B. M. Hegelich*, **C. Huang**, D. Jung[1], S. Letzring, S. Palaniyappan, R. Shah, L. Yin, C. Wilde & H. Wu[2] and others
- Univ. Politécnica de Madrid
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- Ludwig Maximilian Univ.
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- Technical Univ. Darmstadt.
  - **M. Roth**

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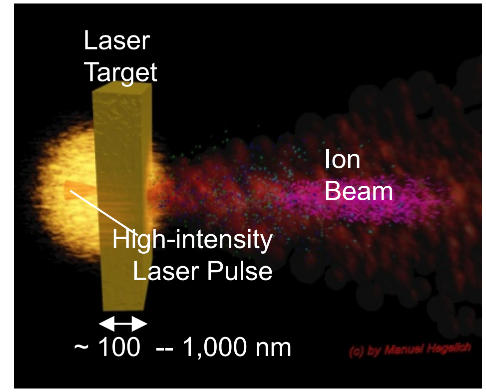
- Trident operations: LANL ICF and Weapons Science Campaigns
- Project: LANL LDRD program, HEDLP Joint DOE-NNSA program

* Now at Physics Dept., Univ. Texas, Austin
[1] Now at Queen's Univ., Belfast
[2] Now at Zhejiang University, Hangzhou, China

Outline

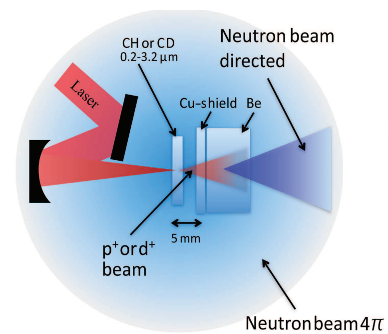
- Physics of ion acceleration
  - Mechanisms

Ion Accel.



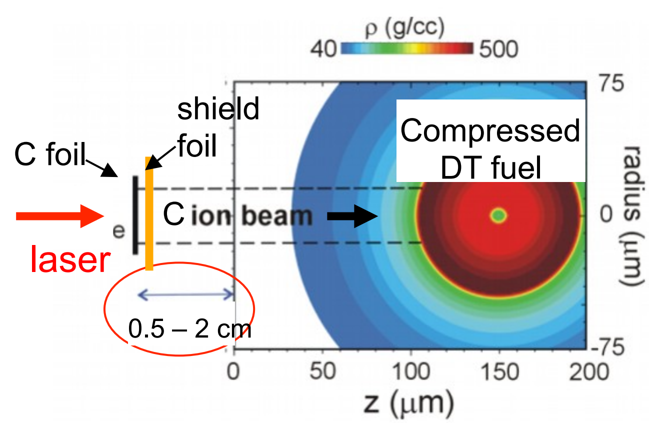
- Applications
  - Neutron generation
  - Mix across sharp interfaces with heterogeneous species
  - Ion-fast ignition
- Summary

Neutrons



Mix

Ion FI



Taxonomy of ion acceleration mechanisms:

Laser-driven ion acceleration mechanisms		Laser-plasma regime	
		Opaque	Relativistically Transparent
Laser target morphology	Thick (micro) foils, solid density	TNSA	
	Thin (nano) foils, solid density	RPA-LS, LICPA	BOA, ISWA
	Near critical-density, long plasmas	RPA-HB, CESA, MVA	

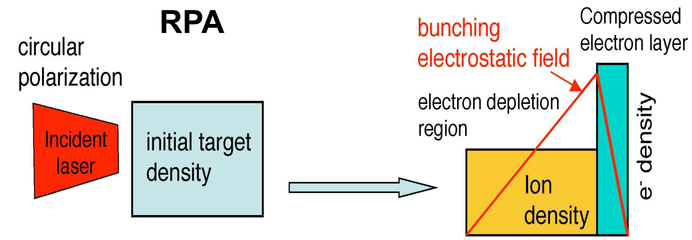
Glossary of laser-driven ion acceleration mechanisms	
BOA	Break-Out Afterburner
ISWA	Ion Solitary Wave Acceleration
RPA-LS	Radiation Pressure Acceleration, Light-Sail Regime
RPA-HB	Radiation Pressure Acceleration, Hole-Boring Regime
CESA	Collisionless Electrostatic Shock Acceleration
MVA	Magnetic Vortex Acceleration
LICPA	Laser Induced Cavity Pressure Acceleration
TNSA	Target Normal Sheath Acceleration

Ion Accel.

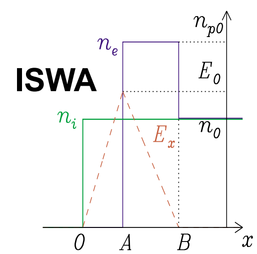
Several *distinct* ion acceleration mechanisms

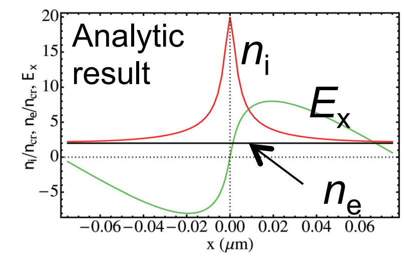
Thin foils, initially **solid-density** plasmas:

- Radiation Pressure Acceleration, light-sail regime (RPA-LS)*
  - Requires **opaque** plasma, clean charge separation (negligible heating, Circ. Pol.)

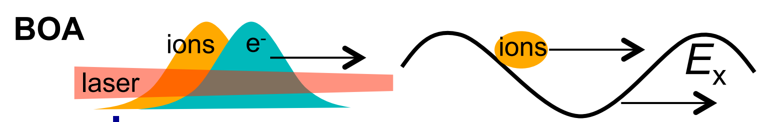


- Ion Solitary Wave Acceleration (ISWA)[1]
  - Charge Sep. ➔ Soliton ➔ **RIT** ➔ ISWA



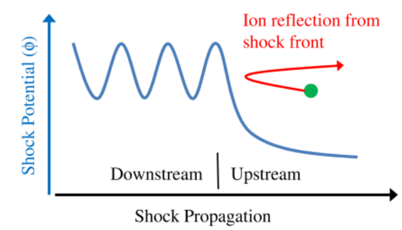


- Breakout afterburner (**BOA**)[2]
  - **RIT**➔ Electron-ion drift ➔ wave ➔ BOA



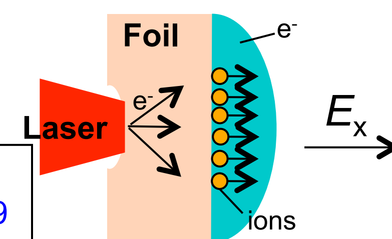
Thick (10's μm), **near n_{cr}** density, opaque plasmas:

- RP – Hole Boring Regime (RPA-HB)[3]
- Collisionless Electrostatic Shock Acceleration (CESA)[4]



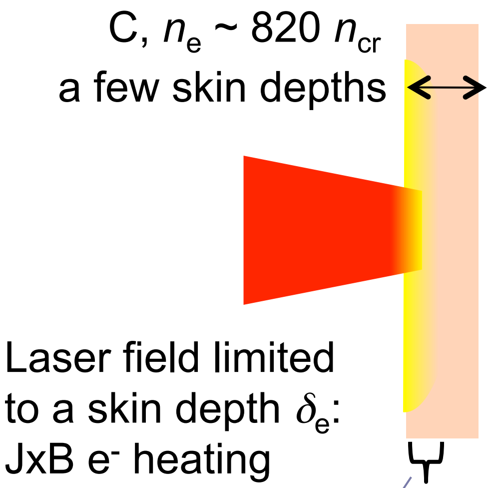
Thick, solid-density opaque foils:

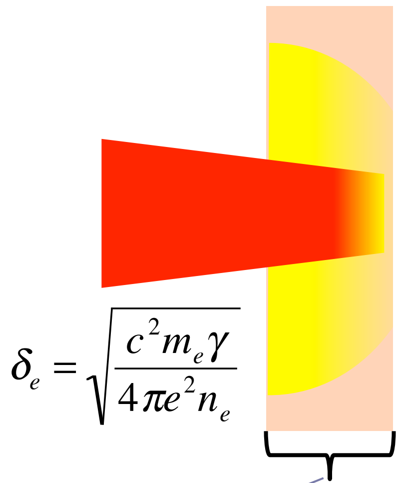
- Target normal sheath acceleration (TNSA)[5]
  - Maxwellian ion energy distribution

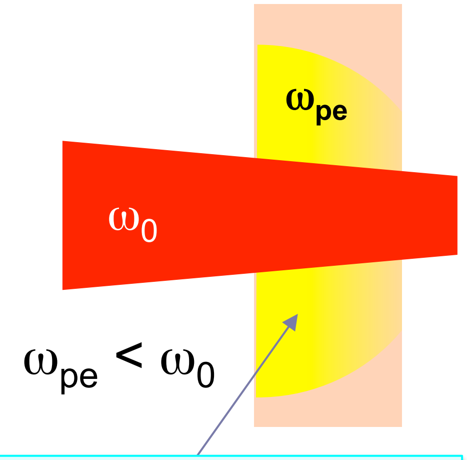


* A Macchi *et al* 2010 New J. Phys. **12** 045013; [1]D Jung *et al* 2011 PRL **107** 115002; [2]L. Yin *et al* 2007 PoP **14** 056006; B Albright *et al* 2007 **14** 094502; [3]T Schlegel T *et al* 2009 PoP **16** 083103; [4]J Denavit 1992 PRL **69**, 3052; [5] S Hatchett *et al* 2000 PoP **7** 2076

Ion acceleration in a new regime: relativistic induced transparency (RIT)



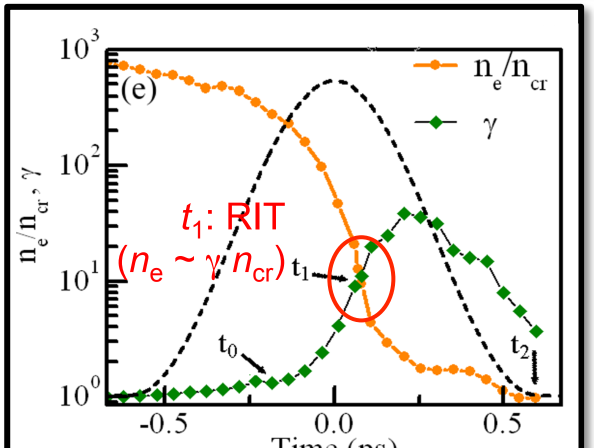




Initially, heating is confined to the front of the target

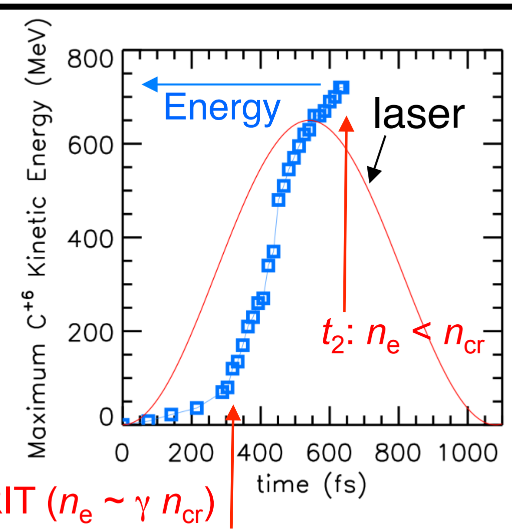
Target expands and δ_e widens – volumetric heating of entire target

Target turns relativistically transparent – BOA ion acceleration



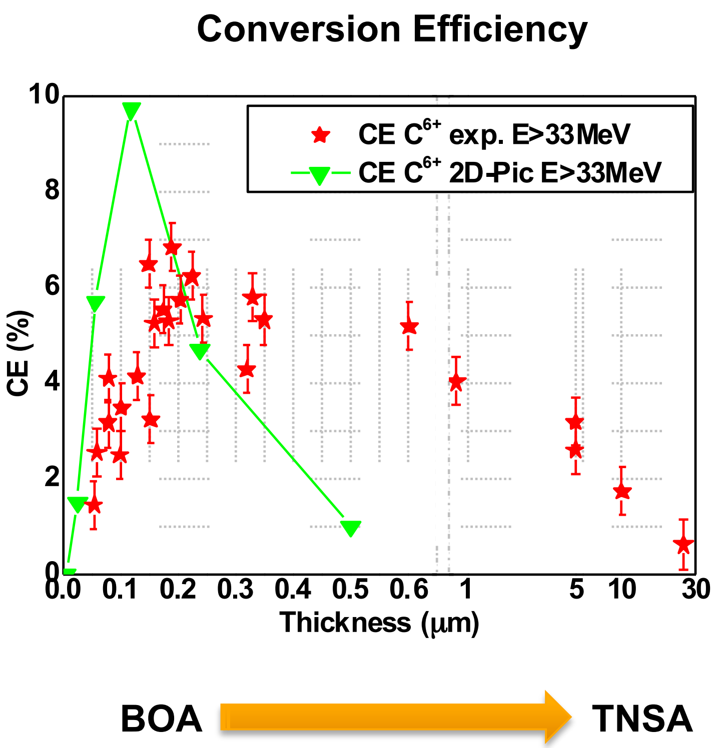
VPIC simulation,
Trident, 100nm Diamond

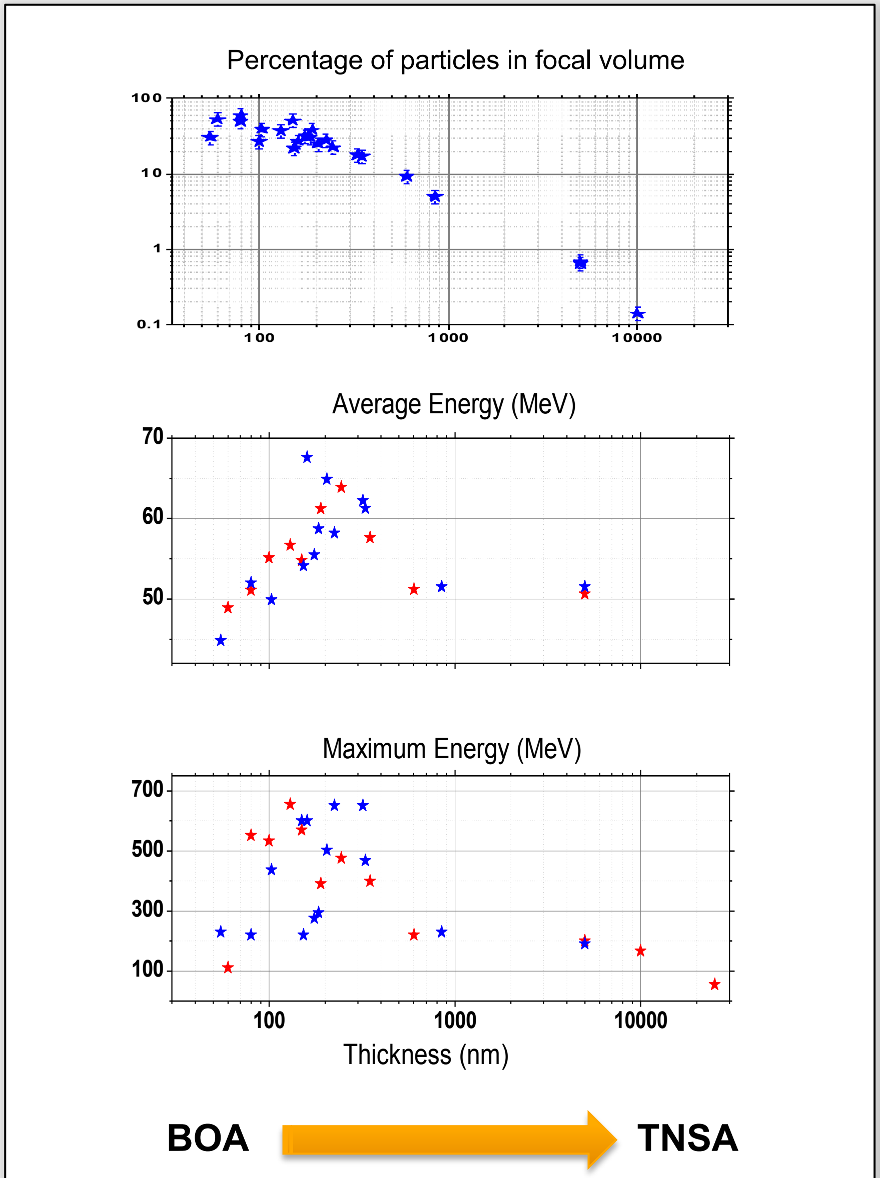
Dominant ion energy gain in PIC simulations during RIT



BOA dependence on thickness: really an optimization of relativistic transparency with with laser pulse length.

- Trident experiments
- Targets: Diamond uncleaned



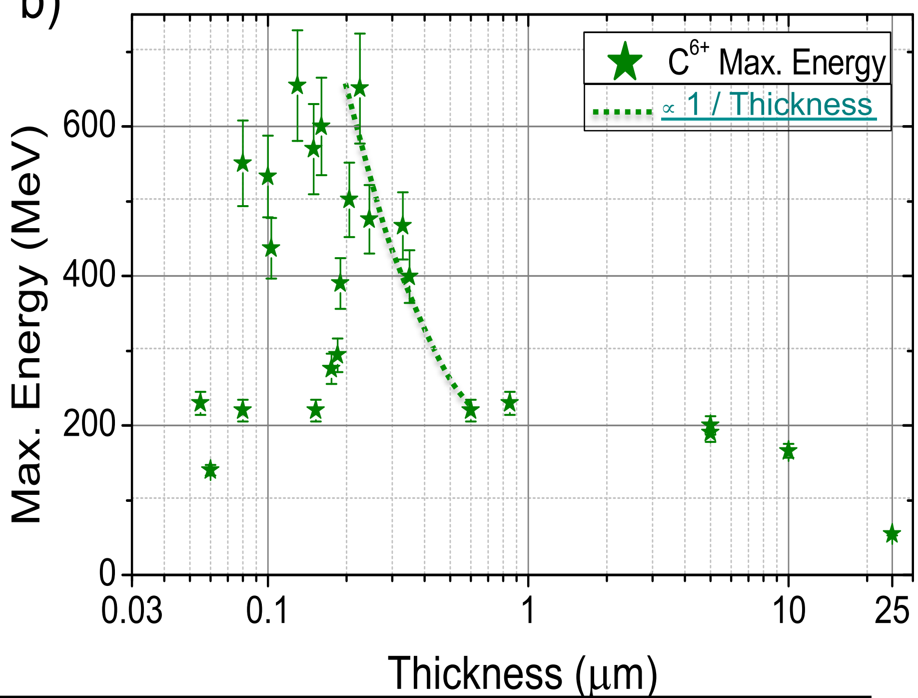


D. Jung, *et al.*, 2013
NJP **15** 023007

Ion acceleration mechanism cannot always be ascertained from limited data scaling alone.

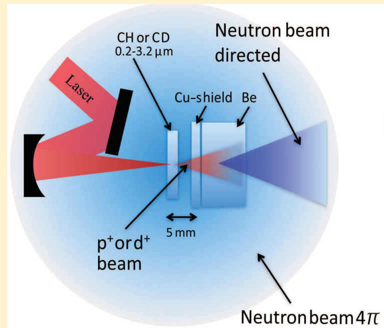
- Consider Trident experiments
  - Linear polarization (vigorous electron heating)
  - BOA mechanism
  - Verified relativistic induced transparency (R. Shah, ICHED, Tues)
- Ion energy from target thickness *l* in RPA is
  $E_{ki} = A\, m_p\, c^2\, \xi^2 / 2[\xi+1]$ where $\xi = 2\, I_L\, t_L / \rho\, l\, c^2$
- In strongly relativistic regime
  $\xi >> 1$ (where we're *not*),
  $E_{ki} \sim a_0^2\, t_L / l$
- **BOA data above optimum thickness mimics relativistic RPA scaling**
- Shows importance of full exploration of phase space (simulations and Exps)

b)

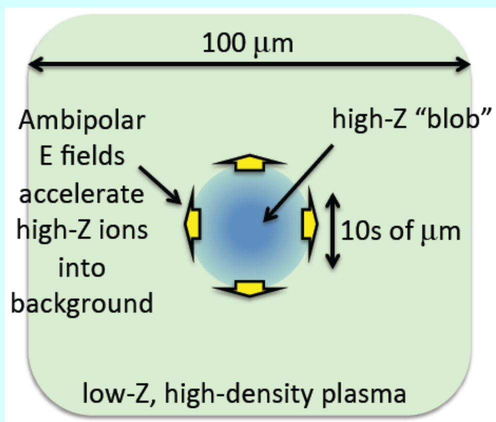


Selected applications enabled by laser-driven ion beams

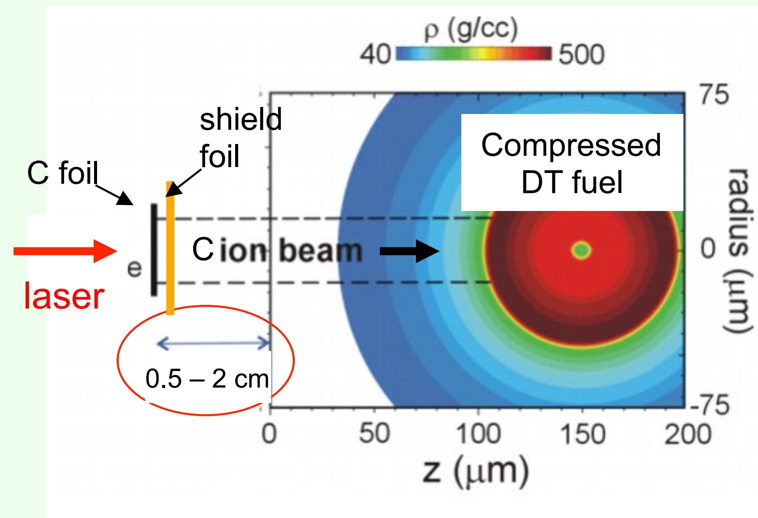
1. Laser-driven neutron beams
   - HED-target probe
   - Active interrogation
   - Materials science

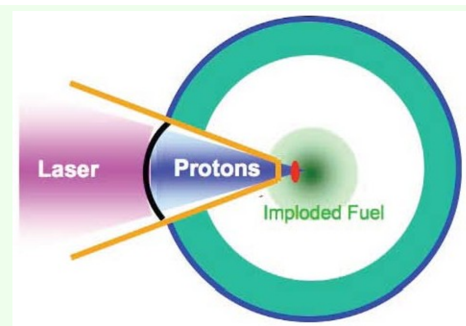


2. Evolution of high-Z or solid particulates in low-Z plasmas
   - Coulomb explosion
   - Mix



3. Ion-driven FI
   - Laser-driven proton or ion beam ignitor of compressed DT fuel





neutrons

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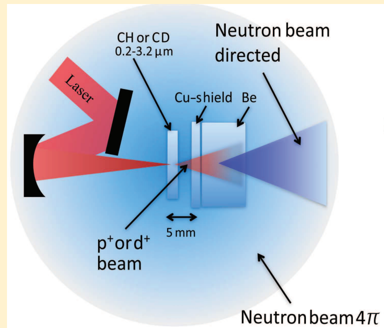

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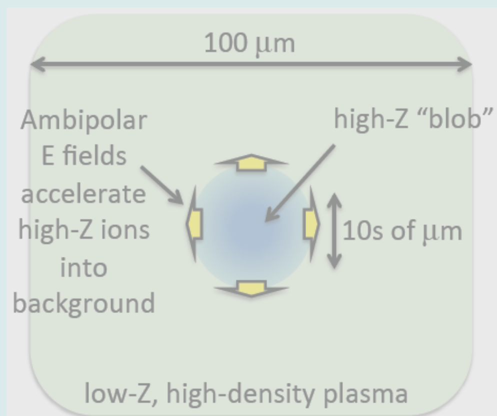

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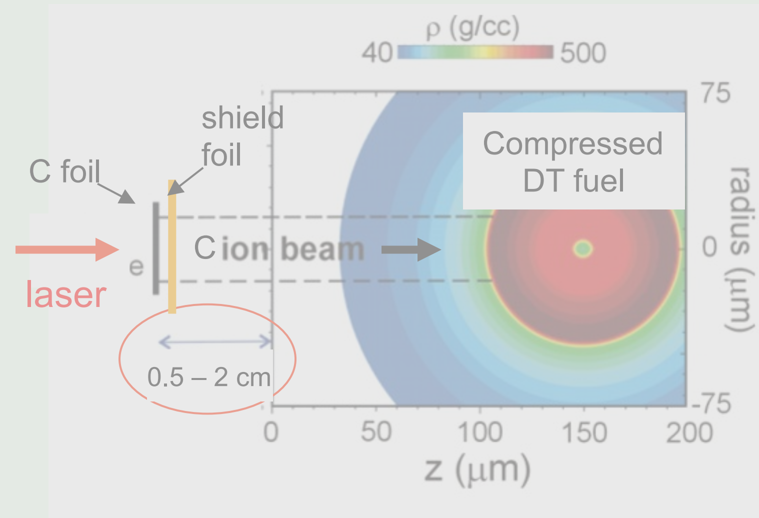
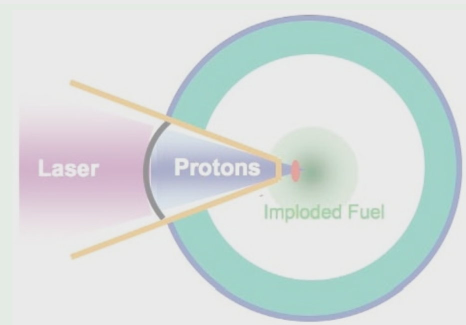
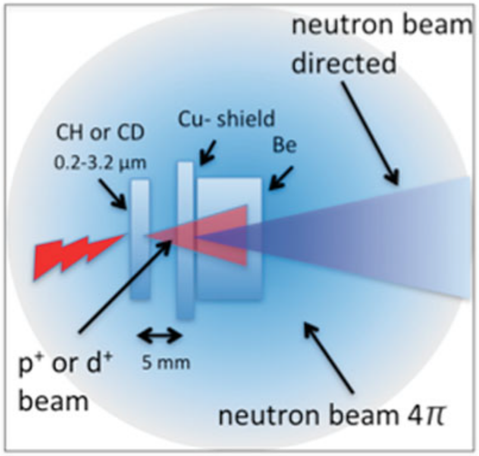
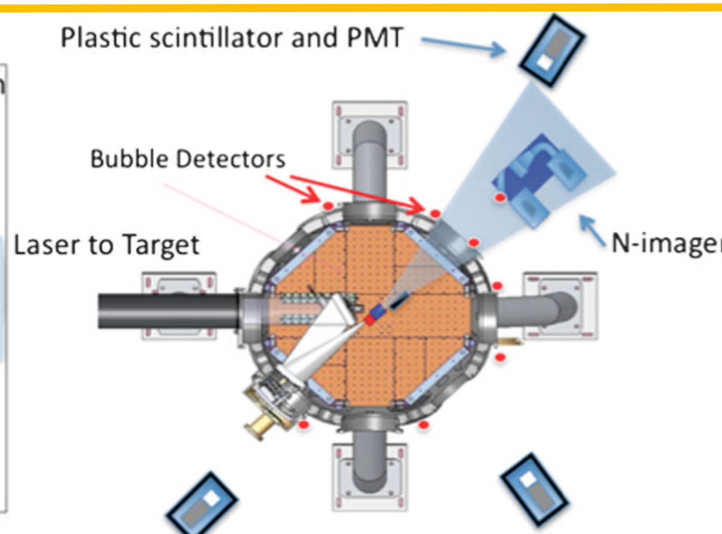




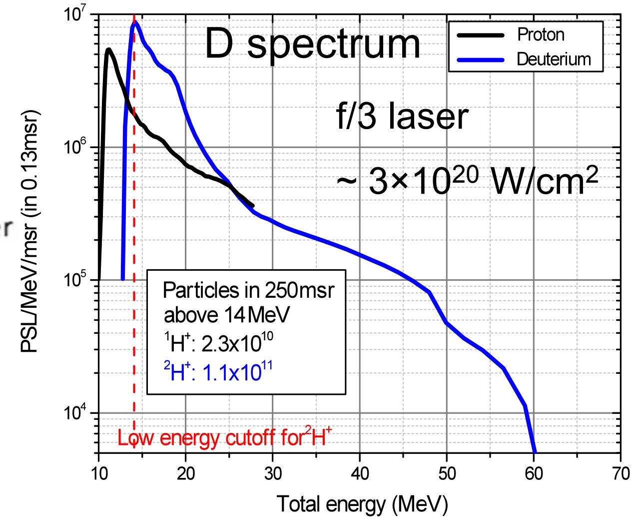
Record neutron production with Trident laser-produced deuterium beam using BOA*

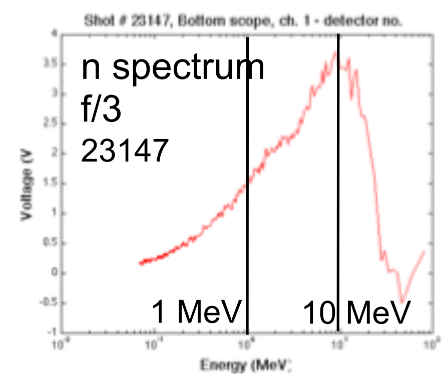


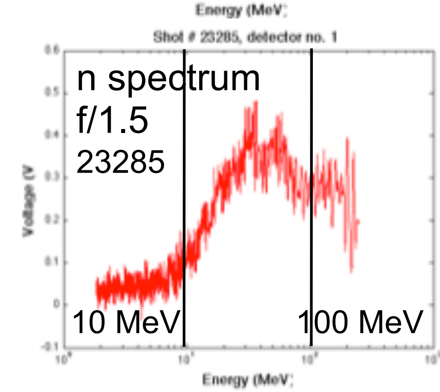
Concept



Setup







- Driven by D beam (BOA mechanism)
- Neutron source ~ ns, forward-directed (~ 0.25 - 1 Srad)
- f/3 laser: record laser-produced yield (~ 10^9 neutrons) & forward fluence (~ 5×10^9 n/strad = 50 neutrons/ μm^2 @ 1 cm), 5-15 MeV neutron energies (~ 10 MeV peak)*
- f/1.5 (~ 1.2×10^{21} W/cm^2): × 10 higher yield and forward fluence, peak energy to ~ 70 MeV, cutoff to ~ 150 MeV*

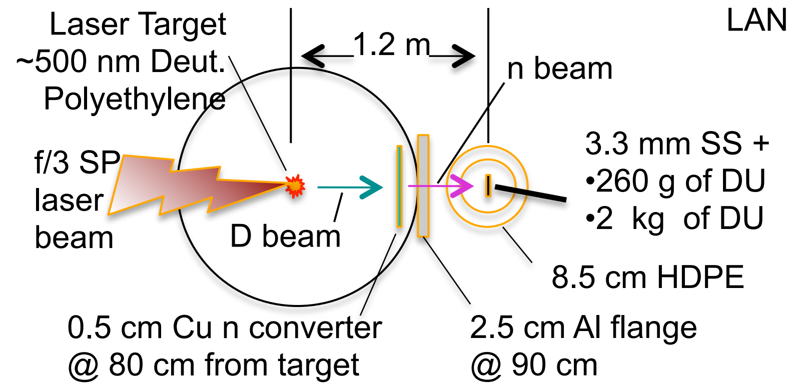
*M. Roth et al., PRL **110**, 044802 (2013); D. Jung *et al.*, accepted to PoP (2013), highlighted by APS, Nature and Physics World neutrons

Laser-based neutron source shown on Trident has demonstrated utility for active interrogation*

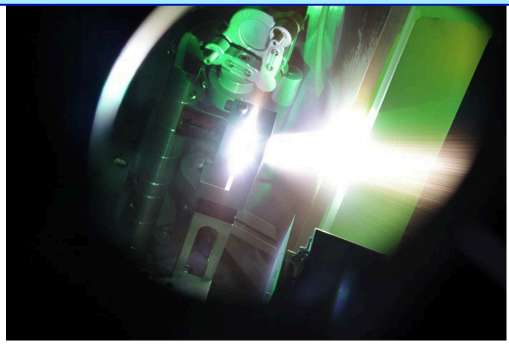
- Fission signatures for nuclear materials:
  - + Delayed and prompt fission neutrons,
  - + Delayed and prompt fission γ's
- Detectors
  - + Bubble & He-3 detectors (insensitive to γ's)
  - + TOF (γ flash & neutrons)
- Converters: Be (mm's from target), Cu (far)
- Application **results** so far:
  - + **Detected DU** with delayed fission neutrons with Be converter (more efficient but farther from sample)
  - + **Detected DU** with delayed fission neutrons with Cu converter (less efficient but closer to DU sample)
  - + **Irradiated Ge samples** ~ 500 n/μm^2 (radiation damage)

Active interrogation experiment on Trident

PI: A. Favalli*
LANL



Using laser-driven neutrons to stop nuclear smugglers
LANL press release 6/4/2013

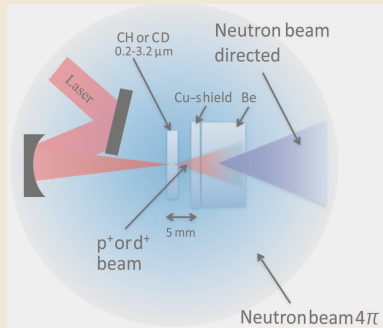


* LANL LDRD Director's Reserve, A. Favalli, PI, Early Career Research

mix

Selected applications enabled by laser-driven ion beams

1. Laser-driven neutron beams
   - HED-target probe
   - Active interrogation
   - Materials science



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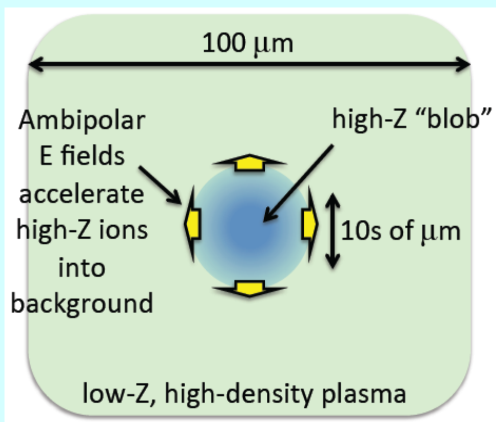
   - Coulomb explosion
   - Mix



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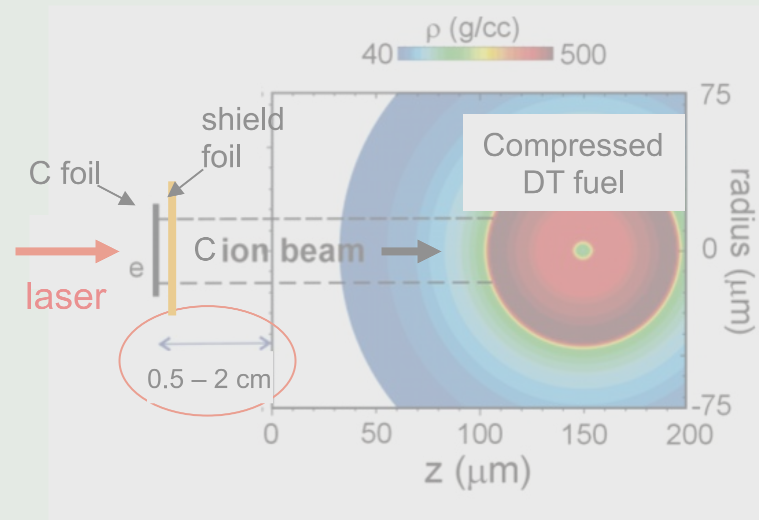
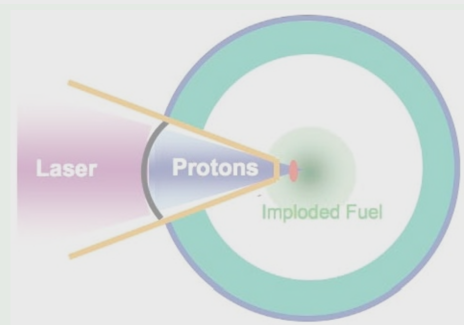
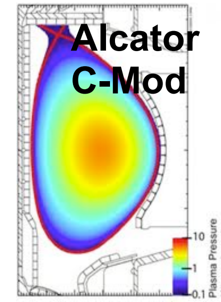


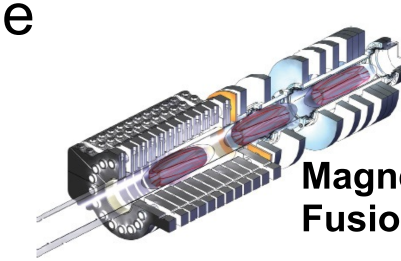


Important to understand breakup & mixing of particulates in dense low-Z plasmas

- Ubiquitous problem, whether initial state is solid particulates or plasma “blobs”
  - E.g., comet tails, semiconductor manufacturing plasmas, tokamak edge plasmas, ICF & MICF implosions, …

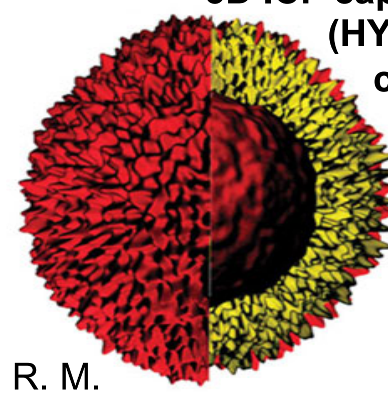


- May be key to understanding “mix” in dense plasmas
  - E.g., certain laser-fusion capsule ablators, Magnetized Target Fusion implosions
  - Atomic versus particulate **mix affects TN-burn**
  - 300-fold increase in temperature increases ion classical viscosity $\Theta^{5/2}$ by factor of ~ 10^6
  - True viscosity is uncertain, may invalidate our physical picture of compressible hydro mix (BHR*)
  - **Electrostatically-enhanced mix** may dominate



Magnetized Target Fusion (MTF)

3D ICF capsule (HYDRA code)

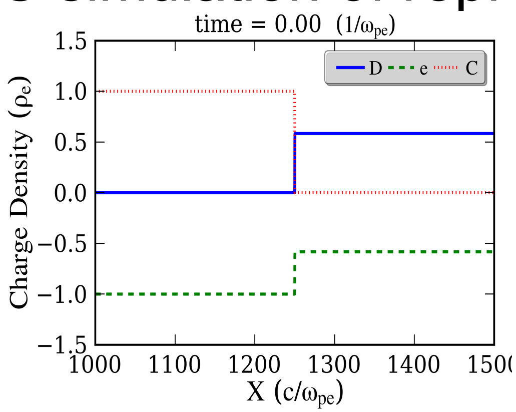


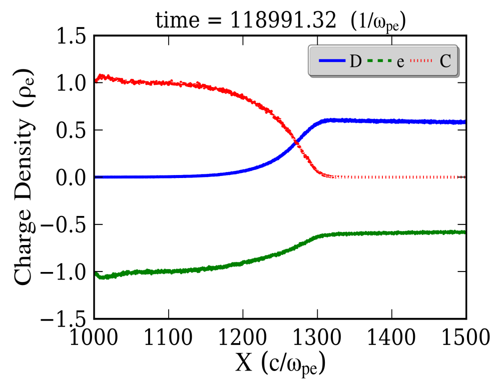
*(Besnard-Harlow-Rauenzahn), D. C. Besnard, F. H. Harlow, and R. M. Rauenzahn, Los Alamos National Laboratory Report No. LA-10911-MS, 1987; A. Banerjee et al., Phys. Rev. E **82**, 046309 (2010)

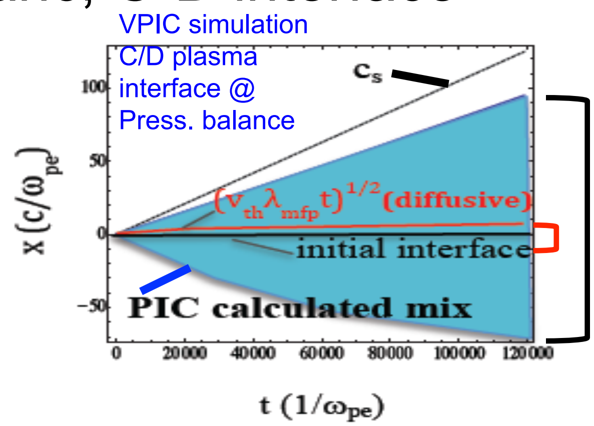
mix

Mixing across sharp interfaces with heterogenous species likely dominated by plasma effects

- PIC simulations show multi-species plasma mixing at ~ sonic (ion-sound) speeds, >> diffusive speeds
  - ***Electrostatically-enhanced mix*** (EEM) requires experimental test
- VPIC simulation of representative case: isobaric, C-D interface



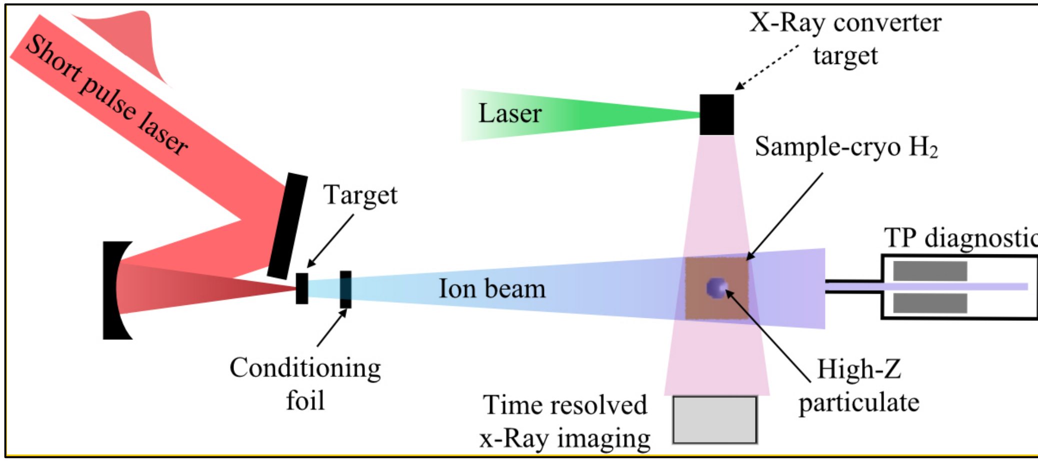




- May dominate “mix” in dense plasmas that affects TN burn
  - Plasma effects can be implemented in mix models like BHR*
- Designed an experiment on Trident to test EEM
  - Use BOA beams to ***isochorically heat*** a sharp interface

*(Besnard-Harlow-Rauenzahn), D. C. Besnard, F. H. Harlow, and R. M. Rauenzahn, LANL Report No. LA-10911-MS, 1987; A. Banerjee et al., Phys. Rev. E **82**, 046309 (2010)

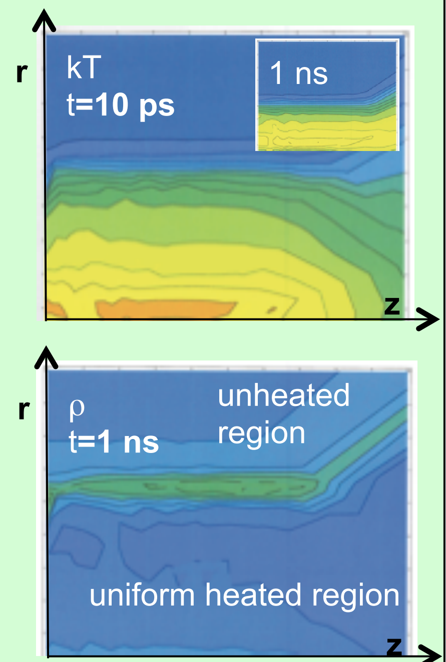
Experiments on particulate evolution in dense plasmas on the Trident short-pulse laser have been designed.



- Frozen H_2 using technique pioneered by TU Darmstadt or CH foam
- High-Z particulate, wire, foil, ~ 10 μm

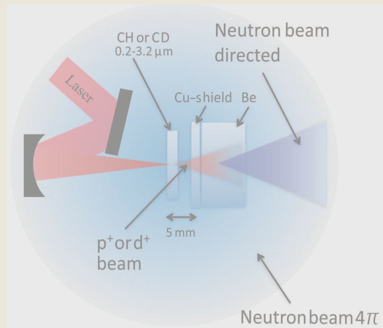
Preliminary data

- Low-Z "background" dense plasma
  - Solid density, T_e ~ 1 -- 20 eV
  - Size ~ (100 μm)^3
  - Frozen H_2, CH_2, …
  - Heated by a Trident proton beam (ultra-thin CH_2 foils, BOA mechanism) NOT ranging in the sample (known energy deposition)
  - Quasi-homogeneous (simulation)

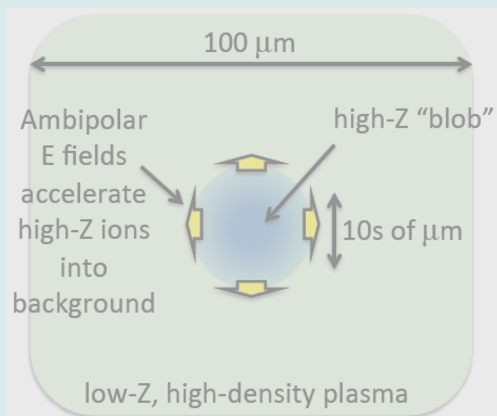


Selected applications enabled by laser-driven ion beams

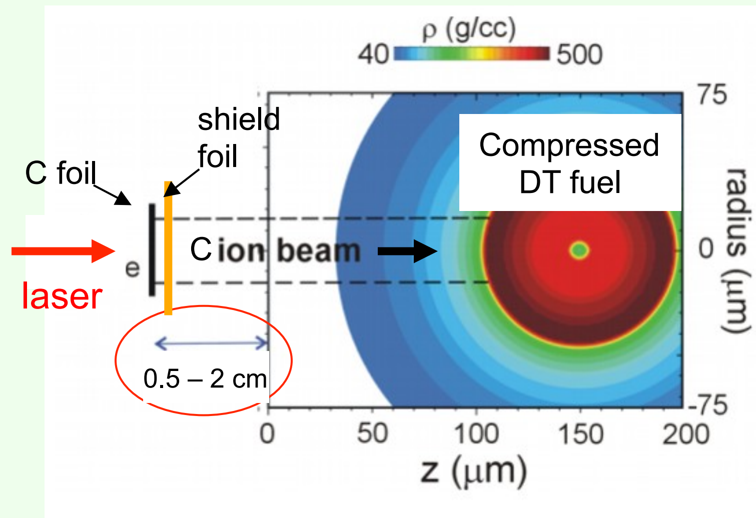
1. Laser-driven neutron beams
   - HED-target probe
   - Active interrogation
   - Materials science

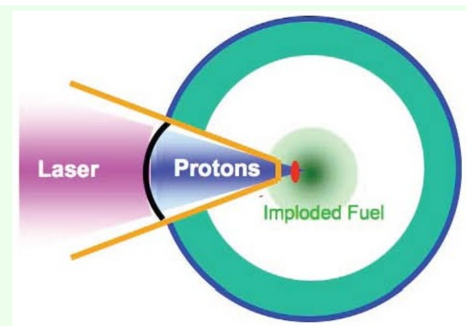


2. Evolution of high-Z or solid particulates in low-Z plasmas
   - Coulomb explosion
   - Mix



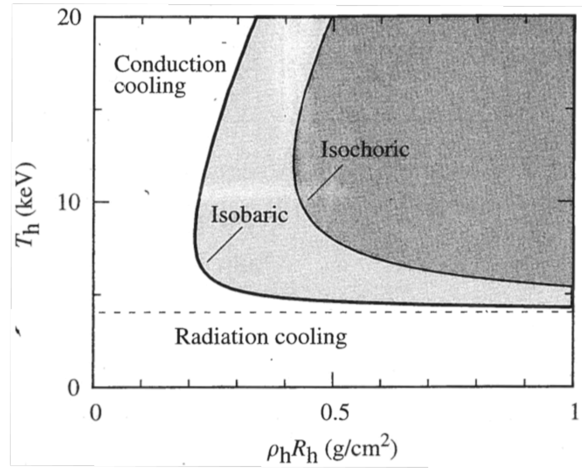
3. Ion-driven FI
   - Laser-driven proton or ion beam ignitor of compressed DT fuel

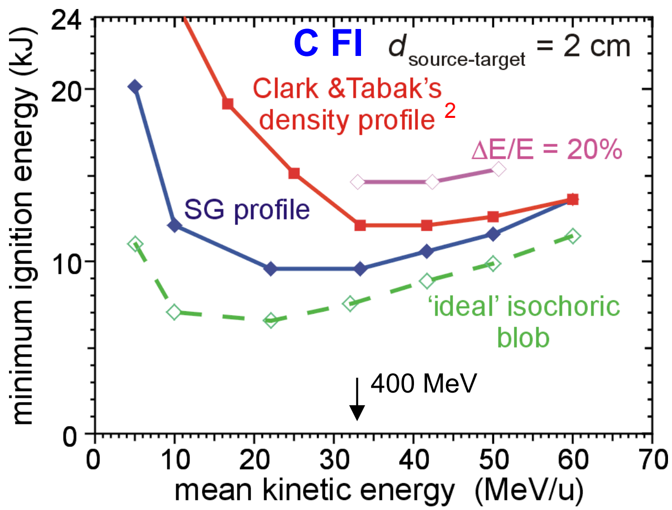


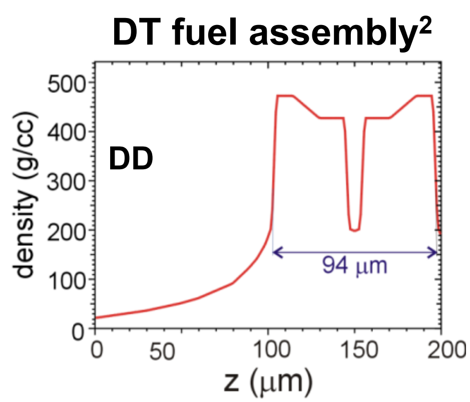


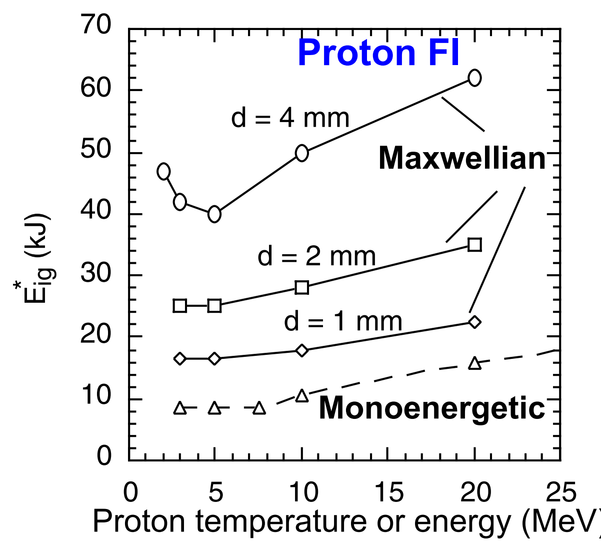
FI of DT fuel assembled with long-pulse laser places specific requirements on ion-beam.*

- Ignition HS conditions set by heating & cooling rates[1]
- Total ion energy required independent of ion species
- Fuel ρr ~ particle range → laser I_L
  - e^- : ~ 1 MeV → I ~ 5×10^{19} W/cm^2
  - **Protons: ~ 10 MeV → I_L ~ 10^{20} W/cm^2**
  - **C: ~ 450 MeV → I_L ~ 10^{21} W/cm^2**







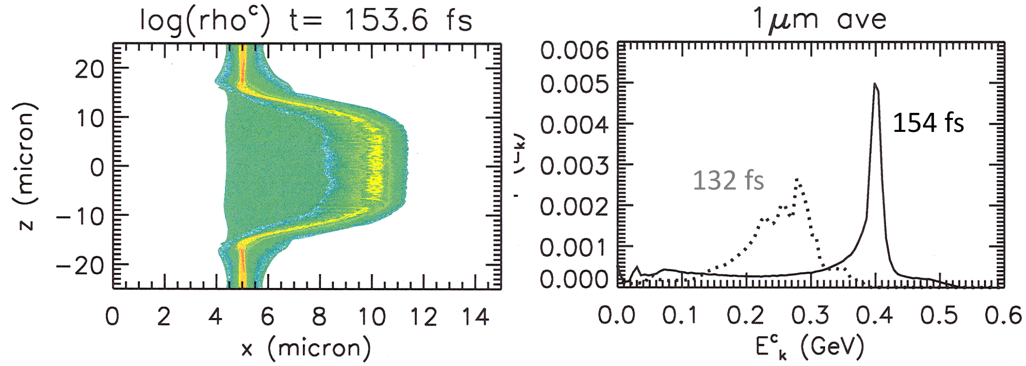


* E.g., S. Atzeni, *et al.*, Nuclear *Fusion* **42**, *L1 (2002); J.C. Fernández, et al., NF* **49**, *065004 (2009)*
[1] *S Atzeni S and J Meyer-Ter-Vehn 2004* The physics of inertial fusion (Oxford: Oxford Univ. Press)
[2] D. Clark & M. Tabak, Nucl. Fus. **24,** 1147 (2007)

RPA → BOA ion FI design

Ion FI

VPIC simulation supporting FI design



Review paper submitted to Nuclear Fusion

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Fast ignition with laser-driven proton and ion beams

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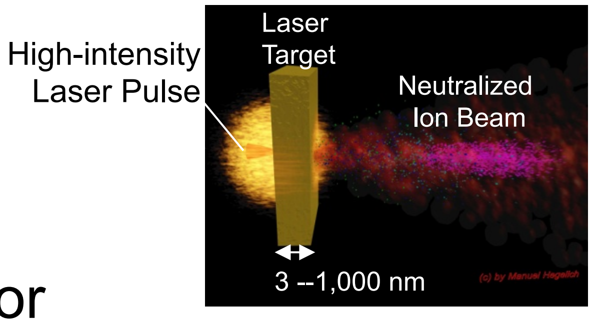
Table 4-1: C FI beam parameters using a hybrid RPA-LS – BOA ion acceleration scheme
[1]=Given, from other modeling, [2]=Chosen, [3]=Derived, [4]=From PIC simulation

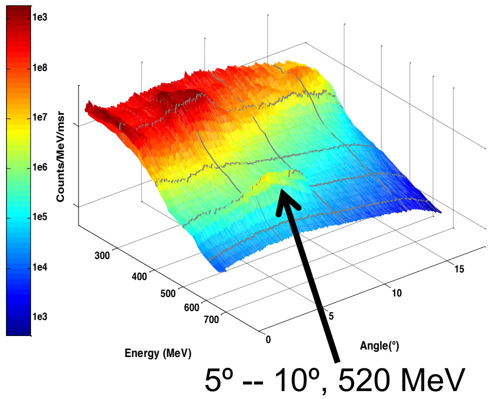
Parameter	**Hybrid**	**TNSA**
E_{ig} [1]	10.5 kJ	12.7 kJ
Ion beam	1.1.1.	1.1.2.
Ion species [2]	**C**	**Protons**
E_{ki} (ion energy)	400 MeV [2,4]	T_h = 4 MeV [1]
δ E_{ki} (ion energy spread), δ E_{ki} / E_{ki}	50 MeV (~ 12.5%) [4]	Maxwellian [2]
γ_i (ion Relativ. factor), β_i (v_i/c)	1.0355, 0.256 [3]	1.0043, 0.092 (T_h)
Target		
Z, A, ρ [g/cm³] [2]	6, 12, 2.0	29, 63.5, 9.0 + 1.8 μm CH_2 layer [3]
l (target thickness)	**30 nm** [2,4]	**20 μm** [2]
η_p (fraction of ions utilized)	0.45 [4]	N.A.
foil travel during t_L	5.5 μm [4] (<< D_L)	N.A.
Source-fuel separation *d*	1 cm	0.5 cm
Laser		
λ_0 (laser wavelength)	1 μm [2]	1.053 μm [2]
Laser polarization	**Circular [2]**	**Linear [2]**
a_0, I_L (laser intensity)	**20, 10^{21} W/cm² [2]**	**9, 10^{20} W/cm² [1], Ref. [52]**
t_L (laser pulse length)	**11 fs rise time + 126 fs flattop to [4]**	**1 ps [3]**
E_L (laser energy)	**120 kJ [3]**	**127 kJ [3]**
η_E (laser-ion energy efficiency)	0.083 [4]	0.10 (Data in Ref. [52])
A_L, D_L (laser spot area, Diam.)	1.21 × 10^{-3} cm² (**393 μm**) [4]	1.26 × 10^{-3} cm² (**400 μm**) [2]

Summary

- Many mechanisms for ion acceleration



- Laser-driven ion beams on Trident used for neutron generation



- Laser-driven ion beams to be used on Trident for electrostatically-enhanced mix studies

- Laser-driven ion beams an excellent candidate for FI